

Fig. 37-1. Erosion along the (A) upper ends of furrows where reduced topsoil thickness allows plowing to mix topsoil and subsoil. Where subsoils are almost white, the effects of these processes becomes visible. (B) Ground level. (C) Aerial of one field. (D) Aerial of several fields.

mixed as well as on areas where the topsoil depth was reduced—but not sufficiently for plowing to mix subsoil with topsoil. Crop yield potential has been reduced 25% by 80 seasons of irrigation furrow erosion on approximately 1 million ha of furrow-irrigated land (Carter et al., 1985).

1. Topsoil Redistribution

Erosion on the upper portion and sedimentation on the lower portion of fields redistributes topsoil. The results of these processes become visible when the color of the subsoil differs from that of the topsoil (Fig. 37-1). The visual evidence of topsoil redistribution would be lacking where subsoil and topsoil are nearly the same color. Furrow erosion can cause a major topsoil redistribution on any field and have a simultaneous, severe, negative impact on crop production.

Typical fields that have been irrigated for about 80 yr are illustrated in Fig. 37-1, showing the color change as whitish subsoil is mixed with darker topsoil. The topsoil distribution varies depending upon the field length and irrigation practice used over the 80 yr. The deepest topsoil areas, resulting from deposition, vary from field to field from about the midpoint to the extreme lower end. Also, there has been a net topsoil loss from most fields, thereby negatively impacting crop yield.

Topsoil depth originally averaged 38 cm in the study area when irrigation began in 1905. The gray topsoil, underlain by a nearly white, caliche and silica-cemented hardpan, varies in thickness from 0 to 30 cm. The hardpan may contain as much as 30% CaCO_3 . Root growth is limited by this hardpan layer over much of the area. Below the hardpan layer is nearly white subsoil with little structure. Before irrigation was introduced, soil below the hardpan was seldom wetted with water from precipitation and was powdery. The natural fertility of the hardpan and the subsoil beneath is low, but can be corrected. Phosphorus requirements to raise available P to adequate levels are high. Zinc is also needed for dry bean production, and N has to be added according to the crops grown. Other nutrients are adequate according to soil test values, and deficiencies have not been noted in growing crops.

The first fields exhibiting the exposure of subsoil were generally those of slopes exceeding 3%, which were among the steepest irrigated. Gradually, fields having lower slopes began to exhibit the color change until today almost all fields with slopes along the furrows $>1\%$ exhibit the phenomenon, as well as some fields with slopes $<1\%$. Studies (Carter et al., 1985) have shown that some fields have lost as much as 90 to 100 cm depth of soil near the head ditch and have deposition as much as 180 cm deep. Commonly, 30 to 40 cm have been lost from the upper ends and 20 to 40 cm have been deposited at some point downslope.

2. Effects on Yields of Major Crops

Investigations indicated that a topsoil depth of about 38 to 40 cm is the minimum depth for maximum yields of all crops in one large study area (Carter et al., 1985). Where topsoils are deeper because of deposition, no signifi-

cant yield increases are found for any crop. In contrast, significant crop production decreases are evident for all crops where topsoil depth is <38 cm. The relationship between topsoil depth and crop yield is approximated by the Mitscherlich-Spillman type equation, $y = a + b(1 - e^{-cx})$, where y is yield, x is topsoil depth, and a , b and c , are constants (Carter, 1988). Dry bean and corn are the crops most detrimentally affected by reduced topsoil depth, followed by wheat. Barley (*Hordeum vulgare* L.) and alfalfa are less severely affected and sugarbeet is least affected by decreased topsoil depth (Fig. 37-2).

The factors responsible for the yield reduction are not known. In efforts to restore productivity, adequate plant nutrients were applied on the many fields studied. None of the crops exhibited nutrient deficiencies. Soil water was monitored in some of these studies and adequately supplied by irrigation to avoid moisture stress. Several organic matter amendments were tried without significant response. The only effective treatment was to replace 30 to 40 cm of topsoil. This restored yields to levels where topsoil had not been removed by erosion.

The soil erosion topsoil redistribution process is progressing in all areas where irrigation furrow erosion is occurring. Impacts on crop yields will not be as pronounced where the crop yield potential of subsoil is nearly that of topsoil. However, the overwhelming evidence indicates that topsoil losses will ultimately lead to serious crop yield losses, because subsoils are generally less productive than topsoils. There are many areas in the western USA

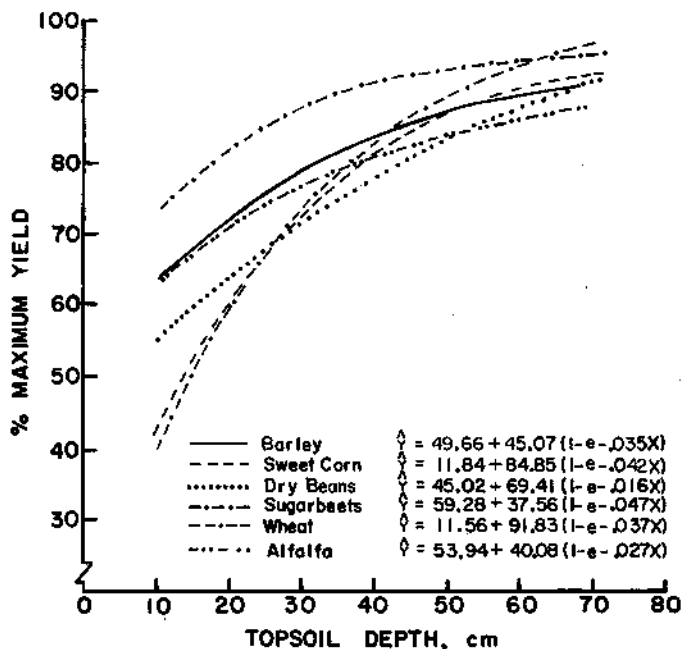


Fig. 37-2. Effect of topsoil depth on relative crop yield for six crops and associated Mitscherlich-Spillman type equations.

where soils have been furrow irrigated for <80 yr. We hope that our findings will stimulate both interest and action towards applying conservation practices to prevent the potential crop yield loss already experienced.

D. Controlling Furrow Erosion and Soil Loss

The concern for improved water quality during the late 1960s, and since that time, stimulated legislation aimed at reducing water pollution and improving water quality. Sediment was recognized as the most important nonpoint source water pollutant from the standpoint of quantity (Robinson, 1971; Wadleigh, 1968). Irrigation return flows were identified as serious nonpoint pollution sources and attempts were made during the 1970s to require permits based upon quality standards before irrigation return flows could be discharged to navigable streams.

Brown et al. (1974) reported sediment balances from two large furrow irrigated tracts. Subsequently, Carter (1976) reviewed the available literature and published some guidelines for controlling sediments in irrigation return flows. Continued interest has resulted in many studies aimed at developing practices to control irrigation erosion and sediment loss. The earlier efforts were on controlling the quality of drainage water after leaving a field. More recently, efforts have been aimed at controlling furrow erosion on the field.

1. Sediment Retention Basins

Basins or ponds constructed in drainage ways to temporarily pond irrigation runoff water can effectively trap sediment and prevent sediment loss into streams and rivers. These basins range in size from about 1.0 ha on main drains to minibasins receiving runoff from only a few furrows. They vary in size and shape, and have been given different names. All are effective, and each type has its best application. Large basins on main drains are usually formed by constructing an earthen dam across a drainage at a suitable site and installing a proper outlet. These large basins trap or remove 65 to 95% of the incoming sediment (Brown et al., 1981; Carter, 1985a). This sediment removal efficiency depends upon the sediment concentration, the particle size of the sediment, and the time required for water to pass through the basin (Brown et al., 1981; Carter et al., 1989a).

Medium-sized sediment retention basins are often excavations in drain ditches receiving runoff water from one or more fields. Their sediment removal efficiencies range from 75 to 95%. Often they are placed at the lowest corner of a field. Unfortunately many of them are undersized and fill with sediment as a result of one or two irrigations. As a basin fills with sediment the water retention time decreases, resulting in a decrease in sediment removal efficiency. The capacity of these basins to remove sediment can change rapidly during a single irrigation as they fill with sediment.

Minibasins are formed by excavating a sequence of small basins along the lower end of a field or by placing earthen checks across the tailwater

drainage ditch. If each basin has an outlet into a separate drainage ditch, sediment removal efficiencies range from 85 to 95%. If the water is allowed to pass from one basin to the next, each successive basin becomes less efficient, and the overall sediment removal efficiency of a series of basins is only 40 to 70%. Often the accumulated flow volume washes out earthen checks and basins (Brown et al., 1981; Carter & Berg, 1983).

A common disadvantage of all sediment retention basins is that costly cleaning is required for them to remain effective. In some instances basins are constructed in low areas and fill with sediment. Fields can then be combined or expanded by rerouting the water after a basin is filled and farming the sediment accumulated as part of the field.

Where farmers own equipment, the sediment may be economically hauled back to the upper ends of fields, or onto a rocky, nonfarm area to expand cropping area.

Sediment retention basins have been an effective educational tool for encouraging farmers to implement erosion and sediment control practices. Few farmers are aware of the quantity of sediment they are losing from their fields until they construct a sediment retention basin and watch it fill with sediment. As they learn how much soil they are losing, they become more interested in implementing practices to reduce soil loss.

2. Buried Pipe Erosion and Sediment Loss Control System

A system comprised of a buried pipe with vertical inlets at intervals to correct the convex field end erosion problem has been developed (Carter & Berg, 1983). The buried pipe replaces the tailwater drainage ditch, and the vertical inlets serve as individual outlets for minibasins formed by placing earthen dams across the convex portion of the field, as illustrated in Fig. 37-3.

The minibasins of this system initially function the same as other minibasins with individual outlets, but with a sediment removal efficiency of 80 to 95%. As these minibasins fill with sediment, their efficiency decreases. At the same time, the convex end of the field is being corrected by filling with sediment. This decreases the erosion rate on the convex end. The sediment deposition depth is controlled by the elevation of the top of the vertical inlet into the buried pipe. The convex end was entirely eliminated by the end of the first irrigation season in all but two of 40 systems studied.

After the minibasins are filled with sediment and the convex end corrected, the sediment removal efficiency of this system decreases to about 70%. However, the sediment involved is from further upslope instead of that generated from the convex end. The sediment load in the water is usually much lower than before. The end of the field becomes flat, and that flat area gradually extends further upslope. Drainage water is carried away through the inlets and the buried pipe, preventing water ponding in these flat areas. Several systems have been in operation for 10 yr and continue to function effectively.

The buried pipe erosion and sediment loss control system has been shown to be a cost-effective practice. Initially, installation costs are higher than for some other sediment loss control practices. But, in contrast to some other



Fig. 37-3. Convex field end showing (A) waste water ditch, (B) operating buried pipe erosion and sediment loss control system during the first irrigation, and (C) convex end corrected after four irrigations.

systems, this alternative increases the productive area of fields by eliminating the tailwater ditch. This also facilitates ingress and egress of farming equipment. With the open drainage ditch, equipment could not enter or leave the field except at constructed crossings, and also had to turn around inside the field perimeter (Fig. 37-3). Eliminating the ditch also improves convenience for cultivating part of the field while another part is being irrigated, and reduces weed problems associated with wet drainage ditches (Carter & Berg, 1983).

Correcting convex ends improves crop production near the lower ends of fields. Many fields with convex ends often erode to the plow depth, resulting in furrow streams 20 to 30 cm below the soil surface, where lateral water movement doesn't reach the roots of small plants. These plants die from drought, and commonly the lower few meters of these areas produce little or no crops. Correcting the convex end eliminates this problem.

Increased crop yields resulting from increasing the harvested area and reducing drought losses increased income sufficiently to pay the costs of installing a buried pipe system in 4 to 8 yr. After that, the increased returns will add to farm profits (Carter & Berg, 1983).

3. Vegetative Filters

A simple, inexpensive erosion and sediment loss control practice is planting a strip of cereal, grass, or alfalfa along the lower end of a field in row crops. These densely planted crops at the lower ends, and in a few cases the upper ends of fields, are called *vegetative filters*. When properly placed and managed, these vegetative filters remove 40 to 60% of the sediment from furrow runoff water when at the lower end of a field and can reduce erosion when at the upper end, but no quantitative data are available for the later



Fig. 37-4. Vegetative filter strip of wheat along the downslope end of a dry edible bean field.

situation. Proper placement and management include planting the vegetative filter close to the drainage ditch and forming the irrigation furrows about one-half the way through the filter strip. Leaving the last 1 to 2 m between the furrow end and the drainage ditch allows the water to spread out through the densely planted crop before entering the drainage ditch. If furrows are made all the way through the vegetative filter, effectiveness is lost. If the furrows are not pulled far enough into the densely planted filter strip, sediment soon accumulates in the upslope side of the strip and water accumulates just ahead of the filter strip. This generally results in eroding a new channel immediately upslope from the strip, parallel to the drainage ditch.

The advantages of vegetative filter strips are simplicity, low cost, and the filter crop can be harvested. An example of a wheat filter strip at the lower end of a dry bean field is illustrated in Fig. 37-4.

4. Placing Straw in Furrows

The effectiveness of straw placed in irrigation furrows for reducing erosion and increasing infiltration was discussed earlier in this chapter. The most effective application of this practice is to apply straw to the steeply sloping segments of the furrows. Berg (1984) and Brown and Kemper (1987) reported significant crop yield increases, infiltration increases, and sediment loss decreases using this approach. Based upon this research, a commercial machine is now available to spread straw in furrows.

The application of straw to furrows should be viewed as an alternative when residues from the previous crop are not available on the field. Where previous crop residue is present, it is better to alter tillage operations to keep some of that residue in the soil surface than to expend the cost and time to bring straw from a source outside the field and spread it in the furrows.

5. Irrigation Management

The relationships among the furrow stream size, furrow slope, and sediment loss were discussed earlier. These relationships illustrate that the larger the furrow stream size, the greater the amount of erosion. One irrigation management tool is to apply the smallest possible stream to accomplish the irrigation. The required stream size is determined by the infiltration rate, slope along the furrow, and the run length. In some instances, reducing the run length by adding a midfield gated pipe may be the best alternative. Other situations may be better controlled by compacting furrows to reduce the infiltration rate. This compacting can be accomplished by traversing the furrow with the tractor wheel or with furrow packers on a tool bar (Kemper et al., 1982; Trout & Mackey, 1988). Another approach is to use surge flow (Kemper et al., 1988), surge flow with crop residues (Evans et al., 1987), or to use a manual or automated stream-size cut-back system (Humpherys, 1971). Automated cut-back systems generally apply furrow streams to one set of furrow until the water reaches the lower furrow ends, then to another adjacent equal number of furrows for the same amount of time. After that

the water is applied to all these wetted furrows simultaneously, resulting in a stream size one-half the original, until sufficient water is infiltrated for crop needs.

Cablegation systems (Kemper et al., 1987) provide for a gradual stream-size reduction. Sediment loss is significantly reduced by cablegation as compared with irrigating with the same stream size for a given set time.

Carefully controlling the stream size in each furrow and selecting either wheel track or non-wheel track furrows are important parameters. The minimum required furrow stream sizes to irrigate adjacent wheel track and non-wheel track furrows are different because of differing infiltration rates (Kemper et al., 1982; Trout & Mackey, 1988). Also furrow-to-furrow variability is 25% greater using gated pipe than using siphon tubes from a cement-lined ditch. Knowing the furrow condition relative to the wheel tracks and knowing the best system for controlling stream size help to make decisions about the stream size to use.

Unfortunately, many farmers operate on a highly regimented time schedule and are limited by the particular irrigation system they have on each field. The general tendency is to apply streams that are erosive to assure that the water transverses the entire furrow length in 2 to 4 h so that adequate infiltrating time to add the appropriate amount of water to the soil reservoir will be certain. When this approach is used, 40 to 50% of the applied water runs off the field as surface drainage, and furrow erosion is often severe (Berg & Carter, 1980).

Changing the direction of irrigating a field to one of less slope can reduce erosion and sediment loss. Also, where slopes exceed 3%, consideration should be given to converting to sprinkler irrigation.

6. Conservation Tillage

Conservation tillage, including no-tillage and reduced or minimum tillage systems, has been applied successfully to rainfed cropland. Until recently, there has been little interest in trying these systems on furrow-irrigated lands. Farmers have long practiced clean tillage to provide clean furrows for irrigation, and it has been unthinkable to consider a tillage system that leaves residue on the soil surface.

Conservation tillage was first introduced to furrow-irrigated land in Washington (Aarstad & Miller, 1979; Miller & Aarstad, 1983). These authors found that conservation tillage significantly reduced sediment losses from furrow-irrigated land. Carter et al. (1989b) introduced no-tillage practices to the Northwest where irrigation furrows are so small that some farmers call them "marks in the soil." These furrows, commonly called *corrugates*, are generally 5 to 8 cm deep and 6 to 8 cm wide at the top. The initial study area in southern Idaho produces garden and commercial bean seed, sugar-beet, and corn as row crops, and alfalfa and cereal as dense-stand crops.

Alfalfa is generally grown in rotation with other crops in this area, and preparing the land for a row crop following alfalfa usually involves 8 to 12 tillage operations, including moldboard plowing when using conventional

methods. The first study (Carter et al., 1988b) demonstrated that wheat and corn could be successfully produced without tillage after killing alfalfa with herbicide (Fig. 37-5). Both winter and spring wheat and silage corn produced the same yields when grown without tillage as when grown under conventional tillage. It was necessary to clean the small furrows to remove rodent mounds and clumps of grass that had invaded the alfalfa and had been killed by herbicide. Wheat was seeded with a conventional, irrigated land-type double-disk drill. Corn was seeded with a double tool bar arrangement with small, chisel-type bull tongues on the leading bar to make a groove in the soil. Flex-type corn planters were attached to the second tool bar, so that they followed directly behind the bull tongue chisels. These no-tillage crops irrigated with better uniformity and required only about one-half as much water as the adjacent, conventionally tilled plots for the first irrigation (Carter et al., 1989b).

Subsequent no-tillage studies have included no-tillage corn following cereal, cereal following corn, and a variety of investigations involving dry bean, corn, cereal, and sugarbeet. The general conclusions from 3 yr of study are that furrow erosion and sediment loss can be reduced 80 to 100% by no-tillage systems and 50 to 80% by reduced tillage systems. Direct crop production costs can be reduced 20 to 30% by using no-tillage practices and 10 to 20% by using reduced tillage practices.

Wide application of conservation tillage on furrow-irrigated land has the potential to reduce erosion and sediment loss 80 to 90%. Such widespread acceptance could almost eliminate the need for the erosion and sedi-



Fig. 37-5. No-till winter wheat growing in a herbicide-killed alfalfa field.

ment loss control practices discussed earlier in this chapter. However, such wide acceptance will require many years of educating farmers, if it is to ever be achieved (Carter et al., 1989b).

III. EROSION UNDER SPRINKLER IRRIGATION

Soil erodes under sprinkler irrigation by processes similar to those reported under rainfall. These are soil particle detachment caused by falling water drops and flowing water, and transport by water drop splash and flowing water (Meyer & Wischmeier, 1969; Trout & Neibling, 1989). However, conditions are often quite different under sprinkler irrigation than under rainfall because: (i) only a small part of a field is receiving water at any given time, (ii) water drops from sprinklers vary considerably depending upon the type of system used, and (iii) sprinkler irrigation is generally applied only when the soil water reservoir needs replenishing for a growing crop or in preparation for tillage. These systems can be properly designed for any particular soil conditions to minimize runoff and erosion.

The most serious erosion under sprinkler irrigation usually occurs with center pivot systems where the application rate at the outer end may exceed the soil infiltration capacity, creating runoff and the potential for erosion. Recently developed low-pressure sprinklers and spray heads also increase the potential for runoff and erosion because the application rate per unit area on the smaller wetting areas must be greater to achieve the same total application. In any case, sprinkler irrigation systems should be designed and operated according to soil characteristics of the field to be irrigated.

A. The Erosion Process

When water drops strike the soil surface, erosion may result. Impacting water drops may detach soil particles from the soil mass. Detached particles are splashed in all directions from the impact point, with a net movement downslope.

Soil particle detachment by water drop impact is proportional to the intensity squared (Meyer & Wischmeier, 1969), or to a product of the momentum and number of drops, both raised to a power (Park et al., 1983). Splash erosion measured by simulated rainfall is proportional to rainfall, or sprinkler intensity to a power that varies with soil type from 1.6 to 2.1 (Meyer, 1981; Park et al., 1983).

An alternative method of evaluating erosion from raindrop impact is to relate it to the kinetic energy of the rainfall. Simulated rainfall with drop diameters of 2.2, 3.2, and 4.9 mm from several heights has been used to study soil detachment from a silty clay, a loamy sand, and two silt loam soils. The regression equation relating soil splash (SS) to kinetic energy (KE), rainfall intensity (I), and percent clay (PC) was

$$SS = 7.50 (I)^{0.41} (KE)^{1.14} (PC)^{-0.52}$$

with a correlation coefficient of 0.93. Kinetic energy was by far the most significant of these three parameters. Adding other soil parameters did not significantly improve the correlation coefficient (Bubenzer & Jones, 1971).

The general erosion potential from various sprinklers can be evaluated by converting the mean drop diameter to kinetic energy using the procedure of Stillmunkes and James (1982). The kinetic energy values can then be used in the above equation to estimate soil detachment by drop splash, and the relative erosivity of any particular sprinkler can be estimated by this method. Recent research has provided limited information on drop size distribution from various sprinkler nozzle designs and the effects of nozzle size or pressure on drop size distribution (Dadio & Wallender, 1985; Kohl & DeBoer, 1984; Kohl et al., 1985).

The preceding discussion concerned the processes governing the sediment produced at a particular site. Sediment transport processes generally determine how much of that sediment is moved from the site. The sediment transported by overland flow depends upon the water application rate in excess of infiltration. The infiltration rate can be reduced by water drop impact and increase the amount of runoff.

When the water application rate exceeds infiltration, water ponds in small surface depressions until they become full. Then water begins to flow downslope as shallow overland flow. This flow seldom produces sufficient shear forces to detach particles, but it does transport some sediment detached by water impact. Usually considerably more soil particles are detached by water drop impact than are transported by this shallow overland flow. Many transport equations have been applied in attempts to describe this part of the overall erosion process (Foster, 1982; Neibling, 1984).

As overland flow moves downslope it concentrates in tillage marks, previous erosion channels, or, as a result of the natural microtopography, it forms new rills. The detachment and transport processes in these rills are similar to those in irrigation furrows. One difference is that the flow rate in rills increases downslope as a result of increasing collection areas, whereas the flow rate in irrigation furrows decreases downslope. Thus, the transport capacity in rills increases until the water flows out of the area receiving water.

Water may flow downslope in rills to an area just previously irrigated, into a dry area not yet irrigated, or along the operating sprinkler line where water is being applied. These three situations can all produce different erosion and sediment transport results. Flows from rills tend to concentrate into fewer, larger channels in natural drainage ways called *ephemeral channels* or *gullies*. Sediment detachment and transport processes in ephemeral gullies are similar to those for rills. Typically, an ephemeral gully will erode downward to a tillage pan or a less erodible layer and then enlarge to an equilibrium width during the first significant erosion event following tillage. Unless tillage occurs, additional erosion will be minimal for subsequent events smaller or equal in size to the event that formed the channel.

Usually the amount of erosion during each center pivot sprinkler irrigation is relatively small because only 30 to 40 mm of water is applied. This amount of water normally will not cause extensive erosion. Most of that water

will infiltrate and not run off the field. The amount of runoff depends on how much the application rate exceeds the infiltration rate. Large amounts of water are applied with wheel line and hand-moved sprinklers, and erosion can be severe.

1. Cohesion Factors

The relationships between soil cohesion factors and erosion are the same under both furrow and sprinkler irrigation. The erosion difference between the two situations involves the forces acting against the soil-bonding forces. The bombardment of water drops on the soil under sprinkler irrigation is a different type of force than the shear force of a flowing stream in an irrigation furrow.

2. Tillage

Extensive tillage that breaks soils into small aggregates also breaks many particle-to-particle bonds and makes the soil more susceptible to erosion under sprinkler irrigation, just as it does under furrow irrigation. Fewer tillage operations generally result in less erosion under sprinkler irrigation. The direction of the final tillage or planting marks can have an important impact on rill and subsequent gully formation under sprinkler irrigation. Such marks up and down the slope should be avoided. This, of course, is not always possible, particularly on rolling topography where much of the sprinkler irrigation is practiced. Tillage and planting marks should follow level contours to the extent possible. No-tillage and reduced-tillage practices can be applied more easily to sprinkler-irrigated land than to furrow-irrigated land because rougher surfaces can be tolerated better under sprinkler irrigation.

3. Surface Condition Effects

The condition of the soil surface can have a major effect on erosion under sprinkler irrigation. Rough, cloddy surfaces have higher infiltration rates. As a result, runoff is decreased or eliminated and erosion is decreased. Overtilled, smooth surfaces are more erodible and generally have lower infiltration rates, greater runoff, and more erosion than rougher surfaces. To be effective as an erosion control measure, soil clods must be large and stable enough to keep infiltration at a high level until the crop canopy covers the soil surface. Such cloddy surfaces can be attained by tilling at selected soil water contents. Also, tilling compacted soils generally results in greater cloddiness than does tilling noncompacted soils (Johnson et al., 1979; Römken & Wang, 1986).

Residue on the soil surface decreases the amount of water drop impact erosion, increases infiltration, and decreases runoff. As a result, overland flow erosion is also decreased by residue on and in the soil surface. Conservation tillage practices increase quantities of surface residues and decrease erosion under sprinkler irrigation.

B. Controlling Sprinkler Irrigation Erosion

Any practice that will reduce the impact energy of water drops striking the soil surface, maintain infiltration, reduce overland flow, and protect against rill and gully formation will decrease soil erosion under sprinkler irrigation. There are several approaches that can be used towards accomplishing these goals. Usually a combination of practices leads to the best results.

1. Irrigation Management

The most important aspect of sprinkler irrigation management is the proper design of the system. Infiltration characteristics of the soil should be evaluated and the results used to select a sprinkler system that will apply water at a rate less than the infiltration capacity of the soil (Bruce et al., 1980; 1985). This is usually easier with wheel line, lateral move systems than with center pivot systems. If the application rate is less than the infiltration capacity and adequate to supply sufficient water to meet crop needs, the only erosion that will occur is that from water drop impact.

The area covered per segment of line increases with distance from the pivot point of a center pivot system. Therefore, to apply the water needed by the crop, the application rate increases with distance from the pivot point. The most serious erosion usually occurs at the outer end of a center pivot system, because the application rate often exceeds that of infiltration.

Once a properly designed sprinkler irrigation system has been installed, it is important to operate it correctly. Operating at pressures different from those designed, improper set times, or operating center pivots at improper travel speeds can also lead to erosion problems.

Another important factor in the design and operation of sprinkler systems is that nozzles or heads should be designed to distribute water drops of the lowest possible kinetic energy to the soil. Water drops with the lowest kinetic energy will cause the least water drop splash erosion and soil surface compaction.

2. Conservation Tillage

Conservation tillage has been practiced for erosion control on rainfed soils for over 20 yr, but only recently have conservation tillage systems been developed for sprinkler-irrigated lands. The same basic systems used for erosion control on rainfed soils will also control erosion on sprinkler-irrigated soils. Such systems are easier to apply under sprinkler irrigation because water can be applied when needed instead of depending upon nature to provide rainwater. For example, deep-furrow drills used to place seed into moist soil on rainfed lands are not required on sprinkler-irrigated land where water can be applied to wet the soils to germinate the seed if necessary.

Conservation tillage systems for sprinkler-irrigated land should leave crop residues on and in the soil surface, provide a rough cloddy surface, and leave

drill or tillage marks on level contours to the extent possible. Crop residues are the most important consideration and tend to mask the effects of the other two parameters.

Crop rotations impact the application of conservation tillage on irrigated land. Usually more crop rotating is required to minimize crop disease on irrigated land than on rainfed land. The cropping sequence should be adjusted if necessary to assure the production of crop residues throughout the rotation. Conservation tillage is then required to maintain these residues on or near the soil surface.

3. Reservoir Tillage

Aarstad and Miller (1973) first demonstrated that making small water storage basins in the soil surface to catch and temporarily store water until it infiltrates was a useful technique to prevent runoff and increase irrigation uniformity. This also almost eliminates erosion under sprinkler irrigation (Longley, 1984). In recent years, tillage equipment has been developed and used effectively for that purpose, and the process of forming the basins has become known as *reservoir tillage*. These small reservoirs function best when they are depressions formed by scooping or pressing rather than being formed by earthen dams in furrows. The latter are not as stable when nearly filled as the former.

Reservoir tillage is generally done after planting the crop but can be done in the same operation for cereals. The tiny reservoirs are placed between rows of row crops, but can be randomly placed in solid cover crops, such as cereals. In either case, once installed, 1 h of land will have thousands of these small reservoirs on the surface (Fig. 37-6). When water is applied by a sprinkler



Fig. 37-6. Reservoir tillage on a potato field.

system, water not immediately infiltrated accumulates in the tiny reservoirs where it gradually infiltrates. Runoff can be prevented or reduced even when the water application rate far exceeds the infiltration rate. Since runoff is eliminated, so are erosion and sediment transport that would have occurred with overland flow. Therefore, erosion is confined to that caused by water drop impact. The use of reservoir tillage has had a major impact on both irrigation uniformity and erosion control under sprinkler irrigation. It compensates for design and operation errors and is of particular importance in areas covered by the outer sections of center pivot systems and on steep slopes. Crop yields have been dramatically increased and soil erosion almost eliminated by reservoir tillage of sprinkler-irrigated land.

IV. SUMMARY AND CONCLUSION

Irrigation-induced erosion began with irrigation and has continued largely unabated until the past 10 yr. The problem was recognized as serious by scientists in the late 1930s and 1940s, but work done then was given little attention by irrigated land farmers. During the late 1960s and early 1970s, sufficient attention was given to water quality that legislation was set forth to control irrigation return flow quality. This stimulated research on polluting sediment sources because sediment was defined as the most serious water pollutant from the standpoint of quantity. This continuing research has provided much-needed information about erosion on irrigated lands. It has now progressed to the point that effective erosion control practices have been developed for irrigated lands.

Although significant erosion can occur under improperly designed and operated sprinkler irrigation systems, the most serious erosion occurs under furrow irrigation.

Soil erosion results when shear forces are sufficient to overcome cohesive bonds between soil particles, allowing soil particles to be broken off the soil mass and transported by flowing water. Both the erosive shear and sediment transporting forces increase exponentially with stream size and flow velocity. Therefore, the furrow stream size, furrow roughness, and the slope in the direction of irrigation are important factors affecting the energy of the stream to exert shear forces. Controlling these factors, is of primary importance in furrow irrigation erosion. Of these factors, humans can control the furrow stream size to a limited extent. However, the furrow stream size must be large enough to provide water to infiltrate along the entire furrow length in a reasonable time to accomplish the purposes of irrigation. Usually, best results can be attained by starting the irrigation with a furrow stream that will reach the lower end of the furrow in 2 to 4 h, and then decreasing it to about one-half the original.

Crop residues in irrigation furrows and rough furrows both decrease erosion because they reduce the kinetic energy of the stream. In contrast, excessive tillage, leaving a fine soil and resulting in smooth furrows without residue, increases furrow erosion.

Cropping sequences affect irrigation furrow erosion by influencing the amount of residue remaining in the soil while producing the subsequent crop. Tillage plays the most important role in the presence or absence of residue. Moldboard plowing, which buries crop residues, is the worst tillage practice commonly used on irrigated land from the erosion standpoint.

Furrow erosion redistributes topsoil by removing soil from the upper reaches of furrows and depositing it downslope. This reduces topsoil depth on the upper 25 to 40% of each furrow-irrigated field, causing serious decreases in crop production.

During the past 15 yr, erosion and sediment loss control technology has been developed and evaluated for furrow-irrigated land. The first practices developed and evaluated were aimed primarily at sediment loss control. These included sediment retention basins ranging in size from 1.0 ha to minibasins receiving runoff water from only a few irrigation furrows. These sediment retention basins remove 65 to 95% of the inflowing sediment from the water. Vegetative filters comprised of cereal, grass, or alfalfa crops planted along the lower ends of fields can filter out about 40 to 60% of the sediment if properly managed.

One important discovery made in the mid-1970s was that large amounts of erosion and sediment loss from furrow-irrigated fields were resulting from mismanagement of the tailwater ditch, thereby creating convex field ends. A buried pipe erosion and sediment loss control system was developed to completely eliminate this problem, as well as remove the tailwater ditch and field access problems associated with it. This system increases the productive area of the field where installed. Increased crop production from that area will generally pay installation costs in 4 to 8 yr.

Placing crop residues in irrigation furrows increases infiltration and reduces furrow erosion. Equipment has been developed to accomplish this straw placement. However, a far more logical approach is to use tillage practices that will leave crop residues on and in the soil surface. Moldboard plowing must be eliminated to avoid burying crop residue.

Reduced-tillage and no-tillage systems introduced to furrow-irrigated land for erosion control in 1978 and 1984, respectively, have great potential for erosion control on irrigated land. A series of studies, beginning in the fall of 1984, have demonstrated that no-tillage and reduced tillage can be used effectively on furrow-irrigated land without causing irrigation problems. These conservation tillage systems reduce soil erosion and sediment loss from 60 to 100%, with the best results coming from no-tillage systems. Direct cropping input costs are decreased 10 to 30% when compared to conventional tillage systems. These savings translate into net profits because crop yields are generally the same as for conventional tillage. Widespread application of conservation tillage on furrow-irrigated lands has the potential to reduce erosion and sediment loss about 85 to 90%. This would also eliminate the need for sediment retention basins, vegetative filters, and placing straw in furrows. The buried pipe erosion and sediment loss control system may still be used in combination with conservation tillage, but the need for such a system would be decreased.

Soil erosion processes under sprinkler irrigation are similar to those under rainfall, with some differences. The amount of water applied by a single irrigation is controlled and it is applied only when needed. Generally, only a small part of the field is receiving water at any given time. Therefore, water flow resulting from runoff is confined. Rill and gully erosion are therefore limited when compared to erosion under rainfall.

The most important erosion control practice for sprinkler-irrigated land is the proper design and operation of sprinkler irrigation systems, which means using reliable soil water transmission and retention data. The use of conservation tillage and the application of recently developed reservoir tillage will also greatly reduce the erosion potential.

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